The snow falls. It falls thickly, saturating the air, swirling on gusts of wind. At times, white, dull white snow striking your windshield is all you can see. You pass by Donner Summit, on I-80, tires skidding slightly on the freshly plowed road. The snow clears slightly, and you are greeted with the sight of a huge machine, a 20-ton snowblower, blowing snow out next to the guardrail. As you continue on, you take note of the perfect straight line of snow along the guardrail. Passing by, you are further surprised by the fact that the driver waved at you, smiling; you get the feeling that his hands are not on the wheel. The goal of PATH researchers is to make this scene real.

Background
A snowblower, aka rotary snowplow, is a massive snow removal apparatus that blows snow high into the air and off the roadway. It is a key component of the snow removal strategy employed by the snow fighters, especially on mountainous highways. To achieve effective removal of the snow built up along the roadside created by either a single snowplow or a fleet of snowplows, the operator needs to drive the snowblower at the edge of the road and often with a very tight tolerance range in order to eliminate the left-over snow “bleeding” back onto the highway. This tactic makes it a difficult task when the snowblower is operated along a guardrail.

An operator generally uses the rear steering joystick to position the snowblower to the appropriate “crab” angle before he reaches a section of guardrail. The operator then drives the huge vehicle body toward the guardrail until the front side of the blower head touches it. He then “tries” to maintain a somewhat constant contact between the blower head and the guardrail using his hands (feeling the pressure), his ears (hearing the contact sounds), and his eyes (looking for the snow poles and obstacles) as he plows forward. Since the blower head can weigh up to 6 tons, it creates a natural oscillation when it hangs in front of the snowplow body. Consequently, the snowblower continuously “bounces” in and out of the guardrail. “Riding on the guardrail,” as the operators...
Dedicated Short-Range Communications (DSRC) is 75 MHz of spectrum at 5.9 GHz allocated by the Federal Communications Commission (FCC) to “increase traveler safety, reduce fuel consumption and pollution, and continue to advance the nation’s economy.” (FCC 1999) It is a promising development supporting vehicle to vehicle and vehicle to infrastructure communication using a variant of the IEEE 802.11a technology (http://www.leearmstrong...). DSRC would support safety-critical communications for collision warnings at high priority, as well as other valuable ITS applications such as Electronic Toll Collection (ETC), digital map update, etc. The versatility of DSRC greatly enhances the likelihood of its deployment by various industries and adaptation by the consumers.

DSRC achieves its versatility by introducing an explicit multi-channel operation model. The 2004 FCC ruling (FCC 2004) specifies DSRC will have six service channels and one control channel. The control channel is to be regularly monitored by all vehicles. Therefore all safety messages are to be sent in the control channel. In the meantime, a licensed roadside unit could use the control channel to announce its services to approaching vehicles (typically non-safety applications) and conduct the actual application in one of the service channels. For example, a roadside unit could announce a local digital map update in the control channel and transfer this data to interested vehicles in a service channel. Table 1 illustrates DSRC data traffic characteristics used in the standards deliberations (Cash 2002, Krishnan 2002, Walrand 2000). Safety messages are in orange.

The mandate to support safety and non-safety communications with priority to the safety communications in a multi-channel operation model makes DSRC unique in networking history in at least two ways. Can DSRC handle time and loss sensitive vehicle-vehicle and roadside-vehicle safety messages either without infrastructure, or with the cheap 802.11 variety? Will there be enough room on the control channel for other non-safety communications such as service announcements? After all, if the announcements are crowded out, the remaining six channels will become unusable.

Secondly, a typical 802.11a radio design allows it to receive and transmit in one single channel at a time. This implies that while a vehicle is off in a service channel downloading a digital map, it may miss some safety messages broadcast in the control channel. How does one enable an 802.11a radio in the vehicle to use the service channels without missing safety messages on the control channel? The PATH wireless laboratory is working on both issues. In this article we discuss the feasibility of supporting safety communications in the control channel.

### A Communication Service for Safety Messages

To evaluate the feasibility of communicating safety messages in the control channel, we have made an assessment of the offered safety traffic. When the offered traffic is large reliability, latency, and CBT deteriorate. In wired networks offered, traffic is measured by the total bits/second produced by all the senders. In wireless networks, the right measure of offered traffic is bit-meters/second (Gupta 2002), i.e., a network able to transmit a bit 100 meters, may not be able to transmit the same bit 200 meters. Therefore the offered traffic depends on the safety message rate (messages/sec), size (bytes/message), message range (meters), and the density of vehicles producing these messages.

Table 2 gives ranges for the parameters determining the offered traffic. Our evaluation is based on these ranges. A vehicle at high freeway speeds (90 mph) moves 2 meters within its lane in 50 msec. This is usually not a significant movement at high speed. Thus messages repeating faster than once...

### Table 1: Typical DSRC Data Traffic Requirements

<table>
<thead>
<tr>
<th>Applications</th>
<th>Packet Size (bytes)/bandwidth</th>
<th>Allowable Latency (ms)</th>
<th>Network Traffic Type</th>
<th>Communication Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection Collision Warning/Avoidance</td>
<td>~ 100</td>
<td>~ 100</td>
<td>Event</td>
<td>300</td>
</tr>
<tr>
<td>Cooperative Collision Warning</td>
<td>~ 100/10 Kbps</td>
<td>~ 1000</td>
<td>Periodic</td>
<td>50–300</td>
</tr>
<tr>
<td>Work Zone Warning</td>
<td>~ 100/1 Kbps</td>
<td>~ 1000</td>
<td>Periodic</td>
<td>300</td>
</tr>
<tr>
<td>Transit Vehicle Signal</td>
<td>~ 100</td>
<td>~ 1000</td>
<td>Event</td>
<td>300–1000</td>
</tr>
<tr>
<td>Toll Collection</td>
<td>~ 100</td>
<td>~ 50</td>
<td>Event</td>
<td>15</td>
</tr>
<tr>
<td>Service Announcements</td>
<td>~ 100/2 Kbps</td>
<td>~ 500</td>
<td>Periodic</td>
<td>0–90</td>
</tr>
<tr>
<td>Movie (2 hrs NFEG 1): 10 min download time</td>
<td>&gt; 20 Mbps</td>
<td>N/A</td>
<td>N/A</td>
<td>0–90</td>
</tr>
</tbody>
</table>
every 50 msec are unlikely to provide significantly new information. On the other hand an update slower than once every 500 msec is probably too slow. Driver reaction time to stimuli like brake lights can be of the order of 0.7 seconds and higher. Thus if updates come in slower than every 500 msec, the driver may realize something is wrong before the safety system.

We also view the message generation interval as the useful lifetime of the message. If a vehicle is broken down, moving slowly, and transmitting its status, the new messages would obsolete the old ones. Thus we assume a message has a lifetime. The network should discard a message after its lifetime and focus on the new message.

Message sizes have been chosen to permit sender or receiver location as per the SAE J1746 standard, GPS, NTCIP hazard codes, and standard protocol headers to be included. Communication is more difficult at high vehicle densities. The 10 meters per vehicle represents the jammed highway. The 30 meters per vehicle represents the highway at capacity. Likewise, the 4 to 8 lane range spans the usual to large roads.

The 300 meter message range corresponds to the comfortable stopping distance of a high speed car. When the road is jammed, neighboring cars will be much closer. Therefore it should not be necessary to send safety messages over the same distance. We assume a top range of 100 meters for jammed roadways, or approximately 10 inter-car distances.

Since 802.11a radios are designed to transmit over distances of 200 to 300 meters, i.e., the upper end of the message range in table 2, we evaluate a single hop, local area communications service. Many safety messages transmitted by a car would be useful to all its neighbors. For example, a stopped vehicle warning would be useful to all approaching vehicles. Therefore we evaluate a broadcast service. The service should broadcast messages to be received within their lifetime with adequate probability. We view the lifetime and reception probability of a messages as its Quality of Service (QoS) requirements.

### Table 2: Offered Traffic Parameter Ranges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message Generation Interval (msec)</td>
<td>50-500</td>
</tr>
<tr>
<td>Message Size (bytes)</td>
<td>100-400</td>
</tr>
<tr>
<td>Vehicle Density (meters/vehicle/lane)</td>
<td>10 (jammed) / 30 (capacity)</td>
</tr>
<tr>
<td>Desired Message Range (meters)</td>
<td>10-100 / 30-300</td>
</tr>
<tr>
<td>Lane Number</td>
<td>4-8</td>
</tr>
</tbody>
</table>

**Design**

In a wireless ad-hoc network there are two obstacles to the reliable reception of messages. If two transmitters within range of a receiver transmit concurrently, their transmissions collide at the receiver. The receiver does not receive either message. To combat this problem one designs a Medium Access Control (MAC) protocol, i.e., a set of rules by which a radio decides when to transmit its messages and when to keep silent. Secondly, even if there is no collision random variations in the wireless channel may attenuate the received power so much that it is swamped by thermal noise. This is combated by selecting the transmission energy to be high enough to reach all receivers within the desired range with high probability, when there are no collisions.

Transmission energy is determined by transmission power, modulation, and error coding. DSRC radios are to be based on the 802.11a radio. In our evaluation we set the transmission energy control parameters to model the 802.11a radio transmitting over a 20 MHz channel at 5.4 GHz and focus on the MAC design problem, i.e., is there a MAC able to deliver safety messages with sufficiently high reliability and small delays?

In unicast communication reliability is enhanced by policies based on receiver feedback. Protocols like RTS/CTS, TCP, or WTP are some examples. These require the sender to learn the identity of its receiver(s). When there are many receivers or the network is highly mobile, meaning the set of receivers can change a lot, learning identities may itself require significant communication. Therefore we have chosen to evaluate ways to enhance reliability without receiver feedback.
Our strategies repeat each message without acknowledgement in combination with CSMA and its variants. Our repetition schemes could be overlayed on CSMA. CSMA is built into 802.11a and enhances the probability of reception without receiver feedback. The following is a brief summary of the various designs we have evaluated.

1) Asynchronous Fixed Repetition (AFR)
2) Asynchronous P-persistent Repetition (APR)
3) Synchronous Fixed Repetition (SFR)
4) Synchronous P-persistent Repetition (SPR)
5) Asynchronous Fixed Repetition with Carrier Sensing (AFR-CS)
6) Asynchronous P-persistent Repetition with Carrier Sensing (APR-CS)

Evaluation Method
We have two methods of evaluation. For the SPR and APR protocols we have developed mathematical expressions for reception probability. These expressions can be processed using Matlab. Secondly we have developed a DSRC simulator. The simulator is based on two others, namely SHIFT and NS-2. SHIFT is a well established traffic simulator. It gives us the trajectories of vehicles driving according to validated models on realistic road networks. We use SHIFT to generate the motion of the radios. This motion is input to NS-2. NS-2 is an open source wireless network simulator released by the computer science department at Berkeley. NS-2 generates the offered traffic and outputs packet reception data. We post-process the data in Matlab to obtain channel busy time, reception probability, and the probability of long burst of failures.

The DSRC simulator is the standard NS-2 release plus
- SHIFT
- the radio model for 802.11a at 5.4 GHz
- the repetition protocols
- a different data structure that changes the run-time of NS-2 from quadratic to linear in the number of nodes. Figure 1 shows the run-time comparisons. This enhancement has enabled us to simulate networks with up to a thousand vehicles.

The exploration of the parameter ranges in table 2 has produced 300 GB of archived data. Both simulator and data are available to others.

Evaluation Results
A safety message is successful if each receiver within its intended communication range receives at least one of the repetitions. Otherwise it is a failure. We evaluate the probability of reception failure (PRF). A low PRF is good.

Figure 2 shows PRF as a function of the number of repetitions for the parameter values in table 3. The convex curves show there is an optimal repetition number. When a message is repeated more than once the PRF drops. On the other hand repetition increases the aggregate number of collisions, implying repetition beyond a certain level should be counter-productive, i.e., the PRF rises. The flatter curves will show the same behavior at higher repetition numbers. The optimal number is different for different message generation rates, vehicular traffic densities, message sizes, etc.

The ChannelBusy Time (CBT) is a measure of the fraction of channel capacity left over for non-safety messages. As the repetition number goes up so should CBT. Thus there is an inverse relationship between PRF and CBT up to the optimal repetition number. As the QoS to the safety messages is raised, the QoS to the others comes down.
The best protocols are the “Fixed repetition CSMA” (AFR-CS) and the “Synchronous Fixed Repetition” (SFR). Figures 2 and 3 show SFR has slightly better CBT than AFR-CS for the same PRF. But, SFR would require a clock synchronization infrastructure while its CBT advantage is not significant. Therefore AFR-CS seems to be the best solution. Note also the PRF improvement over 802.11a is one order of magnitude. Therefore the rest of our evaluation uses AFR-CS. These plots are for the nominal values in table 3. AFR-CS dominates the other protocols (except SFR) for other parameter combinations as well.

Traffic patterns are complex. Figure 4 visualizes one of the SHIFFF traffic patterns we have used. However, figure 5 shows a single number captures this complexity as a good rule of thumb. This is the number of interferers calculated as:

\[ \text{number of interferers} = \frac{\text{desired range}}{\text{meters per vehicle}} \times \text{number of lanes}. \]

In figure 5, varied traffic conditions with the same number of interferers cluster together.

Figure 6 shows the probabilities of bursts of failures of different lengths for the nominal parameters in table 3. As expected the probabilities are small. Thus a receiver is highly unlikely to lose two successive messages.

Figure 7 pulls these various results together to get a sense of the feasibility of supporting safety applications on the control channel. Feasibility depends on a PRF and CBT requirement. Given a PRF and CBT requirement and a combination of parameter values within the ranges in Table 2, our simulation data can show whether it meets the requirements. We do this by assuming the AFR-CS protocol and optimizing the protocol for repetition number, transmission rate, and selecting the modulation and code rate to minimize the power required to cover the desired range. Figure 7 shows feasibility for a PRF less than 1/100 and a CBT less than 50%. For example, the 200 msec message rate, 250 byte message at 140 interferers is feasible. This corresponds to a 4 lane highway at capacity with a communication range of 150 meters. Likewise the 10 meter headway, 4 lanes, and 50 meter range is also feasible since it has the same interferer number.

Summary

Our evaluation exercise shows DSRC safety messaging on the control channel may be feasible. Messages generated every 200 msec is a good rate, since a driver reaction time of 0.7 seconds or higher in near-miss situations means, an on-board safety system relying on communicated messages may be able to recognize the situation faster, thereby providing timely assistance to the driver. The 250 byte message size is also adequate. If a highway reaches its capacity flow between 50 to 55 mph, at these speeds almost all light-duty passenger vehicles are able to easily stop within 150 meters. Thus this may be an adequate value for the desired communication range. Safety system designers have a rea-

Table 3: Nominal Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message Generation Interval</td>
<td>100</td>
</tr>
<tr>
<td>Message Size (bytes)</td>
<td>100</td>
</tr>
<tr>
<td>Vehicle Density (meters/vehicle/lane)</td>
<td>30 (capacity)</td>
</tr>
<tr>
<td>Desired Message Range (meters)</td>
<td>80</td>
</tr>
<tr>
<td>Lane Number</td>
<td>4</td>
</tr>
</tbody>
</table>
Guardrail Damage

commonly put it, creates damage such as tilting, ripping and tearing of the guardrail that can be easily identified by travelers. This damage leads to frequent repairs and replacements of guardrail in the treacherous mountain regions. While guardrails require rehabilitation throughout all the areas maintained by the Department of Transportation, the frequency of rehabilitation due to snowblower damage, typically once every two years, represents a significant cost, thus becoming an opportunity for excellent return through application of advanced technologies such as precision steering control. Application of precision steering control, if successful, will reduce, even eliminate contact of the snowblower with the guardrail, while also improving the repeatability and accuracy of the work performed. Furthermore, the application will increase operational safety by allowing the operator to concentrate on “plowing” and remove the exhausting “drive by feel” as well as reduce the operator’s visual fatigue.

In 2000, the Advanced Highway Maintenance and Construction Technology Center (AHMCT) at University of California Davis, PATH and Caltrans started a pooled fund study, “Development of the Advanced Rotary Plow (ARP) for Snow Removal Operations,” with Nevada and Alaska’s DOT as partners. Caltrans manages the overall project and coordinates resources for field tests and evaluation. AHMCT conducts feasibility studies on the radar warning system, GPS application and rotary protection device. PATH is responsible for the design and development of the ARP automated control system, ranging from the system architecture design, to hardware installation. PATH is also accountable for the development of sensor signal processing and control algorithms, as well as the human machine interface, operator training, and performance evaluation and field operational tests. The ultimate goal of this project is to develop a prototype automated snowblower that will be used by Caltrans operators and can perform real snow removal operations under harsh winter environments.

Various lateral sensing and referencing technologies were investigated for this application; what was found was that machine vision does not penetrate snow, and that the GPS system does not provide sufficient reliability under possible multipath and blockage scenarios. A magnetic marker based sensing system was chosen for the initial implementation primarily because of its high reliability and accuracy (better than 1 cm) under all weather conditions. The mountainous highway I-80 near Donner Summit near Lake Tahoe was chosen to be the first field test site. In 2001, magnets were installed along the eastbound and westbound guardrails of Interstate 80, at 1.2 meter spacing and 4 feet away from the guardrail. Binary coding of the magnetic markers was designed (north pole up vs south pole up) to provide information about guardrail characteristics, such as shoulder side (right or left of the blower) and the end of...
the guardrail. Eight sections of the guardrail were equipped with the magnets for the initial feasibility operation with a total length of 1.46 km between Soda Spring and Kingvale.

Requirements
The initial “performance requirement” from Caltrans’ maintenance seemed to suggest that it is a difficult but straightforward project: controlling

- “Track” accurately along guardrail (2 to 4 inches)
- Support various snow removal operations
- Survive harsh winter environments (snow, ice, salt, water, dirt, wind)
- Simple operation procedure, tolerate operator mistake, easy to train
- Low operator distraction
- Reliable and safe automated operation

During the first winter’s ride-along in a snowblower, we soon realized that accurately controlling a 6-ton oscillatory head on a 20-ton vehicle along the highway shoulder dotted with potholes while pushing and blowing snow and ice was not easy! Let alone that the driver, from time to time, has to adjust the rear steering angle to compensate for various cutting load and road curvature, move the head position and tilt angle to account for different road slope and inclination, as well as change the speed from stop to go to react for various road and snow conditions. The control system must allow the operator to engage automation at ease and to switch it off any time he wants. The system also needs to survive both the operator’s intervention, either intentionally or unintentionally; and the environmental disturbances such as hitting a guardrail or running into an ice patch. Furthermore, during the early literature survey stage, we also found out that little research work exists in the area of snow chain effects and the modeling of a highly nonlinear and under powered snowblower steering assist mechanism. Nevertheless, the project goals dictated that all obstacles needed to be overcome.

Solution
Various control syntheses have been applied to automatic steering control in the past. Many simulation results show tracking accuracy to sub-centimeters range. However, most papers do not aim at designing a comprehensive controller that can be applied to real scenarios with realistic measurement information. The real-world considerations include a vast amount of possible uncertainties as well as the sensitive nature of human perceptions. The good performance presented by many papers often requires at least one of the following: good system models, specific un-modeled dynamics structure, accurate measurements, known vehicle parameters, or ideal steering actuator and mechanism. Some of the controllers perform perfectly under specific design scenarios but with noticeable degradation in others.

As a result, we re-defined the basic automated snowblower system to be able to perform these requirements:

a snowblower at a distance between 2 and 4 inches from the guardrail. An examination of the project objectives revealed that the success of the project would stem on the positive responses of the following questions:

- Does the system reduce or eliminate guardrail damage caused by the blower?
- Does the system effectively support snow removal operations?
- Does the operator like the system and would the operator use the system?

As a result, we re-defined the basic automated snowblower system to be able to perform these requirements:

continued on next page
To date, no automated precision steering control system has been designed to operate under such harsh winter conditions subject to extreme external disturbances. And not only that, but designed also with extensive un-modeled dynamics, under severely “non-ideal” actuating limitations, and requiring transparent “interfacing” with an average operator performing multiple tasks. As the project proceeded, especially under the short time period the snowblower was available to the design team, the researchers soon realized that almost every aspect of the “plant” was far from ideal and that mathematical models often do not portray certain important real characteristics accurately. In an unconventional way, the design of this automated system is more of a “design methodology” than a “design synthesis”. It requires “solutions” to all of the following elements: problem definition, requirement specification, system configuration, hardware installation, software architecture, control algorithms, human machine interface, fault detection and management, and testing and evaluation. Moreover, the above elements were pieced together using a “problem-solving” mindset. The process was instrumental to the successful completion of the design and development of the first prototype snowblower steering control system within the 8-month periods during 2002 and 2003 when the snowblower was accessible to the researchers. Every aspect of the design was almost “right” the first time.

The first prototype automated control was a truly “add-on” system with the following components added to a conventional Kodiak Northwest single engine rotary snowplow with full hydrostatics:

- A computer with a data acquisition unit that processes information and determines control and guidance actions
- Magnetometers underneath the blower body for measuring the field strength of magnetic markers installed under the roadway
- A DC motor attached to the steering column with angular sensors as the steering actuator
- A yaw gyro and speed sensor for measuring vehicle yaw rate and speed
- Driver Vehicle Interface (DVI) consisting of the local electronic circuit, a toggle switch, LED displays and an audible unit

The key software components that collectively constitute the necessary intelligence of the automated system are:

- Reliable signal processing algorithm that provides consistent location estimates despite large vehicle movements and enormous environmental irregularities
- Smart steering servo that firmly carries out the steering command under highly nonlinear mechanical characteristics and unpredictable disturbances
- Robust high-gain “lane-keeping” controller that accurately follows the “magnets” under all operational conditions even without slope and curvature information
- Adaptive exception controls that cope with any imaginable “abnormal” scenarios such as sudden potholes, guardrail touching, actuator saturation, unknown limit cycle oscillations, operator mistakes or interventions
- A dependable “transition” controller that executes “on-demand” transitions between automated and manual control under all operational conditions
- A simple and transparent DVI that facilitates clear operator state awareness and prompts timely and correct responses under both normal and emergency scenarios
- A fault detection and management system that detects system irregularities and provides a warning while at the same time conducting preventive actions

The effectiveness of the design effort is evident, for example, in the DVI system, the first such system developed by PATH for an automated vehicle. The core of this DVI is four status LED’s: GREEN when the system is ready for transition; WHITE when it is under driver’s control; BLUE when it is automated; and RED when there’s a problem. The operator simply approaches the guardrail the same way as he always does. A separate supportive guidance indicators display the current “tip location” of the blower head. Once the blower reaches within its appropriate crab angle range, the system is ready to transition to automation, and the GREEN LED will be lit. Once the GREEN status LED is on, the driver can switch to automated control any time he wishes by pushing down the AUTO switch. With a soft acknowledgement sound, the BLUE status LED will then be lit, indicating the blower is now under automated steering control. The operator can resume manual control by pushing the MANUAL switch or by overriding the steering wheel at any time. A flashing RED LED, with an emergency sound beeping simultaneously, signals the driver to take over control immediately.
Reactions
With efforts from the dedicated team members, the first prototype system was ready for trial on March 2002. Two Caltrans snowblower operators were the first to be introduced to the system on April 30, at the Kingvale maintenance yard. The trial used a set of cones to simulate a guardrail with magnets installed under the pavement 4 feet away. The simulated guardrail course included a right curve, sloping pavements and potholes. The drivers experienced the transition from manual to auto steering and back to manual steering with varying speeds and were able to keep the blower head at a distance within 4 inches of the “guardrail” without touching them. In the questionnaires the operators filled out after the trial, they responded to the question:

Having seen the automated system, did your opinion on how valuable it could be for snow blowing operations change? Please indicate what your opinion was before and after seeing the system work.

Driver 1: “Yes – opinion before: a waste of time and money, opinion after: system works, helpful to driver”
Driver 2: “Could be an asset in poor visibility, definitely cut down guardrail damage.”

On October 15, 2003, Caltrans conducted an ARP ride-along Demonstration to more than 30 stakeholders from 3 states at Kingvale using a simulated guardrail under various operational scenarios for over 3 hours. All participants were impressed by the performance. We were especially surprised by the positive comments from those who had previous experience working with snow removal equipment. Comments like:

“It works!” and “Having the system keep the front in (on the guard rail) while the operator can use the rear steer for different snow accumulations and (road) turns is just what we need,” were timely encouragements to us in facing the next big challenges: blowing snow along I-80! New “realities”, such as huge potholes on a tilted shoulder, “missed” or displaced magnets, hitting big ice packs, snow chains, and driver interferences, would show up and challenge the system when the snow hits the blower, and we hope we are ready to face and overcome them.

Deployment
Looking forward, we hope to conduct the first field-testing and evaluation along the I-80 guardrails before the end of this winter. Based on the data collected, human factor studies, and the operators’ feedbacks, we will upgrade and redesign the prototype system during the summer and fall of 2004. Full winter field operational tests are then anticipated during winter 2004/2005. However, when the questions like “where can we buy it?” or “when can we get it?” kept coming out, we got a sense that we might be successful enough to have some people look over the performance feasibility question and start asking about the question of deployment feasibility – the eventual objective of Caltrans. The issues of maintainability, cost effectiveness, reliability, and commercialization feasibility will then have to come to the forefront. As for now, the $50 k price tag on the current prototype equipment installed on the snowblower seems to be a good start. Meanwhile, we have work to do before this winter ends.

Acknowledgments
Support from the following Caltrans members are crucial for the success to date: Robert Battersby, Bob Meline, and Larry Baumeister from DRI; Kirk Hemstalk, and Jerry Lander from District 3. The experience and advice from the snow fighters at Kingvale provided the project with the best guideline that we could have had. Last but not least, the following technical team members are the real heroes for the project. They created also the snowplow guidance system and the bus precision docking system. Software: Bénédicte Bougler and Paul Kretz. Hardware: Dave Nelson, Thang Lian, and Bart Duncil. Human factor: Joanne Chang. Steering actuator: Fanping Bu.
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sonable chance of designing safety systems within these offered traffic limits.

On the other hand a PRF of 1/100 and 200 msec of delay is not the best of possible worlds. Our evaluation assumes all vehicles transmit all the time. If communication becomes a general way of learning the vehicle neighborhood then this will be the case, i.e., each vehicle will regularly transmit its position, velocity, turn signal status, etc., for the benefit of others. We think this paradigm represent large offered traffic. Therefore, ours may be worst-case PRF’s, not observed at low market penetrations.

One could respond by attacking the problem on the network side or safety system side. On the network side, research on more complex protocols might make the entire parameter space in table 2 feasible at PRF’s of 1/1000 or better. On the safety system side research could produce more precise requirements for safety applications. Finally, one might develop an architecture able to evolve from the QoS levels offered by repetition at initial stages of deployment to higher levels of QoS in later years derived by greater investment.

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The authors gratefully acknowledge help from Daniel Jiang, Jeffrey Ko, and Tony Mak.

References
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California PATH Wins “Best of ITS: Research Program” at ITS America 14th Annual Meeting and Exposition

During 2003, California PATH completed a three-year program of research, development and demonstration on the application of a variety of Intelligent Transportation System (ITS) technologies to enhance the effectiveness of Bus Rapid Transit (BRT) operations. This program included testing of three transit buses operating under automatic control at highway speed on an High Occupancy Vehicle (HOV) facility, as well as precision docking at two different types of bus stops. Visitors from the ITS and transit communities had the opportunity to observe the testing in August 2003, in conjunction with a national workshop on automated BRT and other transit innovations. By riding in the experimental vehicles, they were able to directly experience some of the benefits of the use of the technologies, which enabled them to better understand how rapidly the technologies are advancing and becoming available for public deployment in the near term. Research that includes full-scale demonstrations such as this is needed in order to convince the customers for the ITS technologies that they are indeed feasible, beneficial, and attractive to the public. PATH gratefully acknowledges the contributions of its partners on this project: Caltrans Division of Research and Innovation, Caltrans District 11, San Diego Transit, and the San Diego Association of Governments (SANDAG).

For the complete story including photos and videos of the 2003 demonstration see: http://www.path.berkeley.edu/PATH/Research/Featured/102803/san-diego.html

For the ITS America news release “2004 Best of ITS Awards Honor Industry’s Top Innovators “ go to http://www.itsa.org under show session news.

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